Tectonophysics, 74 (1981) 263--282
Elsevier Scientific Publishing Company, Amsterdam — Printed in The Netherlands


# MORPHOTECTONIC ANALYSIS OF THE HAZARA ARC REGION OF THE HIMALAYAS, NORTH PAKISTAN AND NORTHWEST INDIA

VIVIEN GORNITZ and LEONARD SEEBER

*Goddard Institute for Space Studies, New York, N.Y. (U.S.A.) and Columbia University, New York, N.Y. (U.S.A.)*
*Lamont-Doherty Geological Observatory, Columbia University, New York, N.Y. (U.S.A.)*

(Received June 25, 1980; revised version accepted September 18, 1980)

## ABSTRACT

Gornitz, V. and Seeber, L., 1981. Morphotectonic analysis of the Hazara arc region of the Himalayas, north Pakistan and northwest India. Tectonophysics, 74: 263--282.

In the Hazara arc region of northern Pakistan, some of the active basements structures buried below a thick, detached sedimentary layer are inferred from the distribution of lineaments and the drainage patterns, as viewed in Landsat satellite imagery and from river profiles.

A prominent set of NW-trending lineaments seen on satellite imagery, coincides approximately with the southwest or updip side of the Indus—Kohistan seismic zone (IKSZ) — the most active basement structure of the region, even though this structure is buried beneath and decoupled from a 12 km thick sedimentary layer. The IKSZ has been interpreted as an extension of the Himalayan Basement Thrust, and is also associated with a prominent topographic "step".

Knickpoints on major rivers in the region lie on or north of the IKSZ. All Indus River tributaries, examined north of the IKSZ, show prominent knickpoints, while two tributaries draining south of the IKSZ have no knickpoints. These results suggest ongoing uplift above and north of the IKSZ, and are consistent with the tectonic model obtained from the seismic data.

Another prominent lineament set is detected along the north—south section of the Indus River. This set is probably related to the Indus River horst—anticline and associated reentrant.

One of the two highest lineament concentrations occurs at the intersection between the NW-trending IKSZ lineament and the N-trending Indus River lineament. The other is along the west bank of the Indus Valley, 25 km north of Tarbela Dam.

A topographic ridge (Swabi—Nowshera ridge) appears to be forming along the west side of the Indus River, in the Peshawar Basin. The rising ridge is ponding the Kabul River upstream of Nowshera, where the drainage is braided.

## INTRODUCTION

An objective of this paper is to analyze Landsat satellite imagery for lineaments and stream drainage patterns that may represent the subtle surface

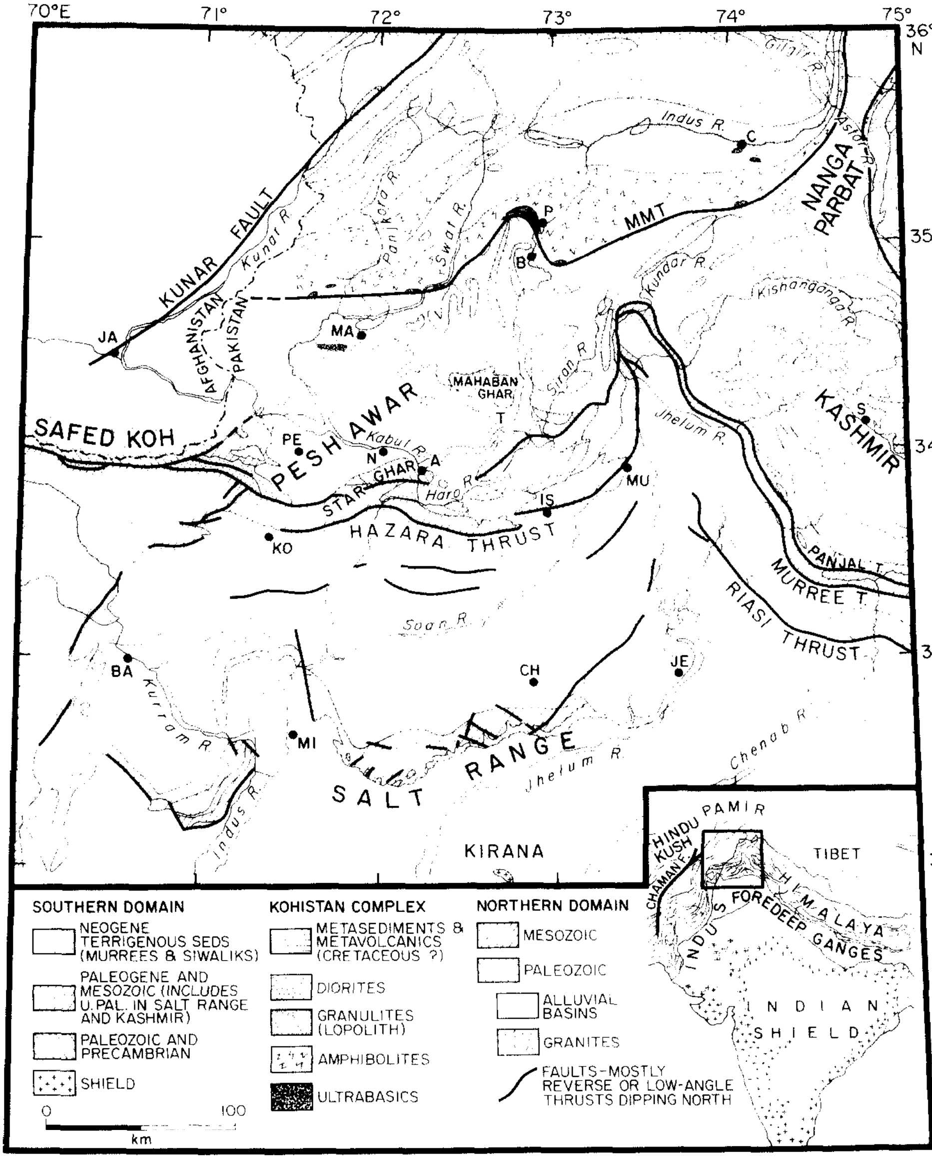



Fig. 1. Geologic sketch-map of the northern Hazara arc and Kohistan. Adapted from: Tahirkheli and Jan (1978), Bakr and Jackson, (1964), Calkins et al. (1975), Gansser (1964), Desio (1964), and Powell (unpubl. data). The Kohistan complex is bound to the north by the Kunar fault, and to the south by the MMT. Tahirkheli et al. (1979) interpret this unit as an island arc obducted onto the southern (Indian) domain. The northern (Asian) domain lies north of the Kunar fault. Names of towns: *A* = Attock, *BA* = Bannu, *B* = Beshem Qila, *CH* = Chakwal, *C* = Chilas, *IS* = Islamabad, *JA* = Jalalabad, *JE* = Jhelum, *KO* = Kohat, *MA* = Malakand, *MI* = Mianwali, *MU* = Murree, *N* = Nowshera, *P* = Pattan, *PE* = Peshawar, *S* = Srinagar, *T* = Tarbela.

expressions of active basement structures concealed beneath the sedimentary cover in the western Himalayas.

Mapped surface structures in the Hazara arc region bend sharply from northwest to south at the Hazara—Kashmir syntaxis, and continue southwest to west along the Hazara arc into northern Pakistan (Fig. 1; Wadia, 1931; 1961; Calkins et al., 1975). The strike of these surface structures contrasts sharply with two parallel, NW-trending, deep-seated active seismic zones (Seeber and Jacob, 1977; Armbruster et al., 1978; Seeber and Armbruster, 1979). These are the Indo-Kohistan seismic zone (IKSZ) and the Hazara lower seismic zone (HLSZ). The IKSZ is the straight extension of the Himalayan thrust earthquake belt through and north-west of the Hazara—Kashmir syntaxis. This belt is associated with basement underthrusting toward the northeast (Seeber et al., 1979). The HLSZ, about 70 km southwest of the IKSZ, is primarily a right-lateral strike-slip fault. Slip on both the HLSZ and IKSZ contributes to the N—S convergence at the western end of the Himalayan front. The sharp contrast between surface and deep-seated tectonic regimes is produced by a nearly horizontal detachment at a depth of 12—17 km. This detachment prevents the structures buried beneath, in particular the IKSZ and the HLSZ, from reaching the surface (Fig. 2).

Although the seismically active, deeply-seated faults cannot be linked to specific surface fault traces, they are expressed by prominent topographic "steps", where the more elevated side is on the upthrown or northeastern side of the buried faults (Seeber and Jacob, 1977; Armbruster et al., 1978).

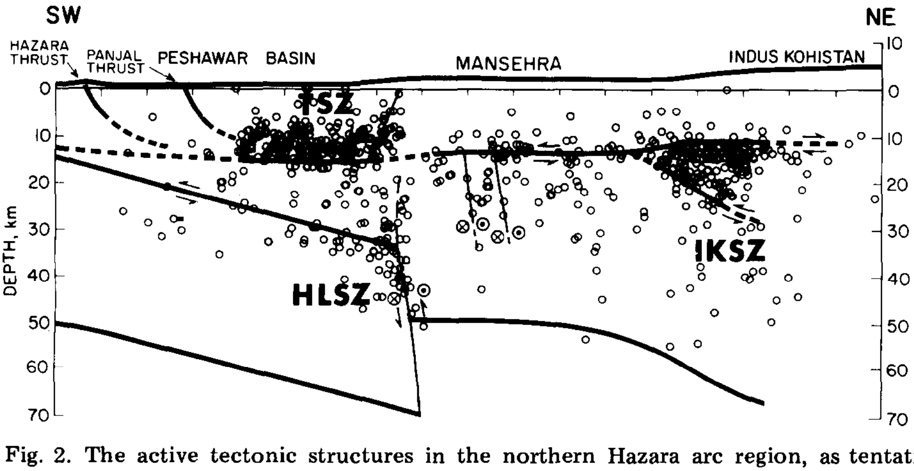



Fig. 2. The active tectonic structures in the northern Hazara arc region, as tentatively deduced from seismic network data. The section is located in Fig. 3. *IKSZ* = Indus—Kohistan seismic zone; *HLSZ* = Hazara lower seismic zone; *TSZ* = Tarbela seismic zone; dot in circle = motion toward viewer; cross in circle = motion away from viewer. The sense of movement indicated by the arrows is deduced from composite fault-plane solutions, except for the detachment slip above the IKSZ. The lower boundary of the crust is not constrained by the data. From Seeber et al. (1980).

The topographic step at the IKSZ continues along the belt of thrust earthquakes of the Himalayan arc and separates the Lesser from the High Himalayas. Thus, topography rather than surface structure is a more reliable indicator of active basement faulting along the Himalayan front.

If active basement structures influence topography, then other morphological features should be similarly affected. In this study we examine river profiles, drainage patterns and lineaments on Landsat satellite imagery in the Hazara arc region. We then relate the anomalies in these patterns to the buried active fault systems, as determined from the seismicity.

*Landsat image interpretation*

The Landsat satellites orbit the earth at an altitude of 920 km, in a circular, sun-synchronous, near-polar orbit and provide synoptic views of the ground that cover an area of 185 km on a side. The ground resolution cell is approximately 60 by 80 m. The imagery used in this study is produced by one of two imaging systems on board of the satellites. The multi-spectral scanner (MSS) consists of an oscillating mirror that scans the terrain perpendicular to the direction of spacecraft motion. Reflected radiation is fed into an array of six detectors, in each of four spectral bands: green (0.5—0.6 $\mu$m), red (0.6—0.7 $\mu$m) and near-IR (0.7—0.8 and 0.8—1.1 $\mu$m). A thermal IR band (10.4—12.6 $\mu$m) has been added to Landsat 3. The data is digitized and transmitted via S-band radio to ground-control stations, where the digitized data is stored on magnetic tape and also converted to images.

Landsat MSS imagery of the Hazara region (Fig. 1) is examined for lineaments that can be diagnostic of surface traces of faults. The linear features are mapped on transparent overlays directly from 1 : 1,000,000 MSS band 7 and false-color composites. Because some linear elements could be artifacts introduced by variations in solar illumination, multiple coverage was ob-

TABLE I

Landsat data, Hazara region, north Pakistan and northwest India

| Scene ID | Date | Center coordinates | Sun elevation | Sun azimuth | MSS band (s) |
|---|---|---|---|---|---|
| *Peshawar Basin* | | | | | |
| 1065-05175 | 9/26/72 | 34°31'N 72°24'E | 46° | 140° | 7 |
| 2493-05005 | 5/29/76 | 34°33'N 72°17'E | 59° | 106° | 4, 5, 7 (color comp.) |
| 2673-04552 | 11/25/76 | 34°32'N 72°15'E | 27° | 147° | 4, 5, 7 (color comp.) |
| *Hazara syntaxis* | | | | | |
| 1118-05130 | 11/18/72 | 34°11'N 73°36'E | 31° | 152° | 7 |
| 1442-05105 | 10/8/73 | 34°36'N 73°43'E | 43° | 144° | 7 |

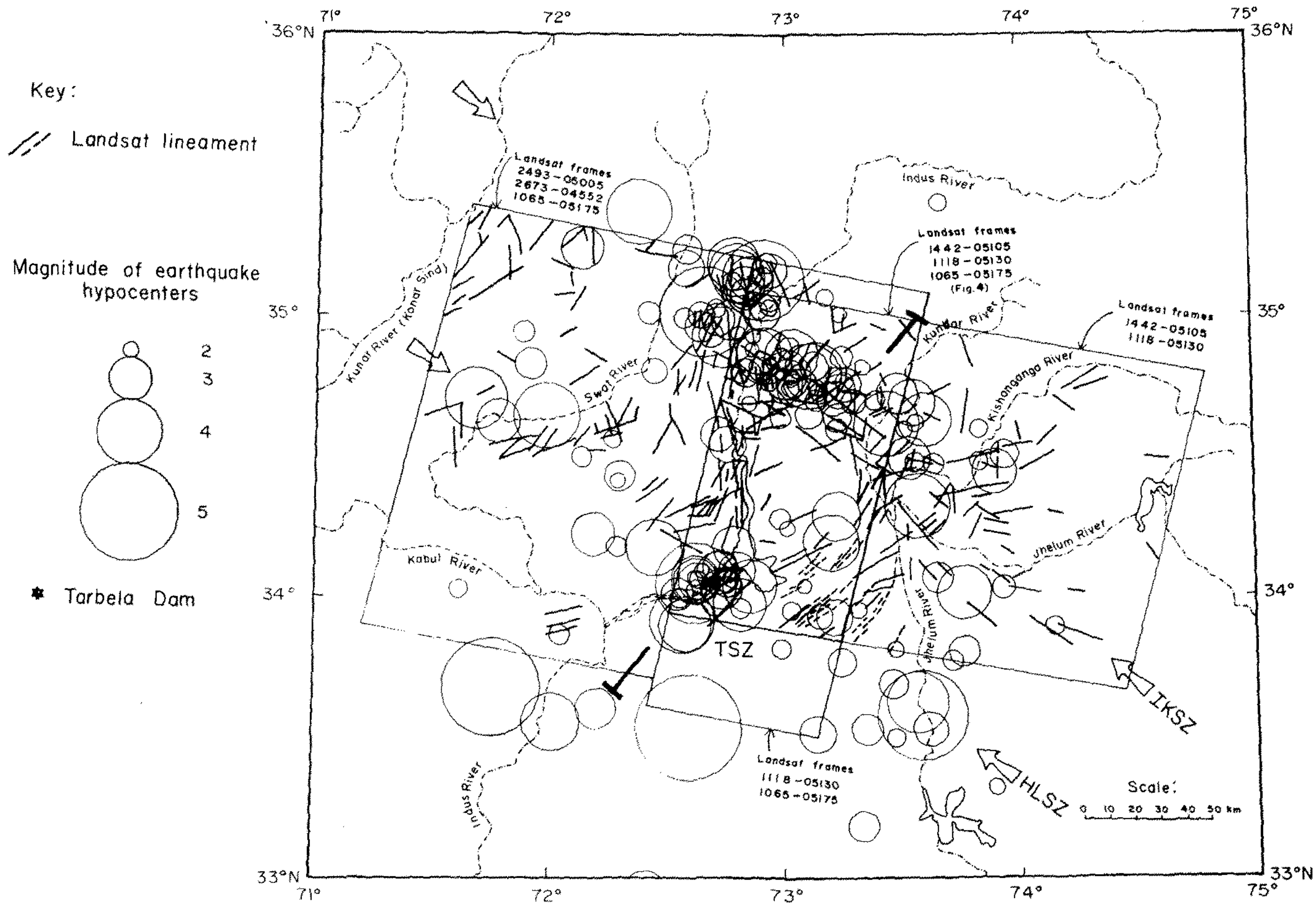



Fig. 3. Composite Landsat lineament map superimposed on a seismic map obtained from the Tarbela network (*hypocentral* depths between 12 and 30 km only); Aug. 16, 1973 to Aug. 22, 1976. Diameter of circle is proportional to local magnitude, for events with magnitudes $\geq 2$.

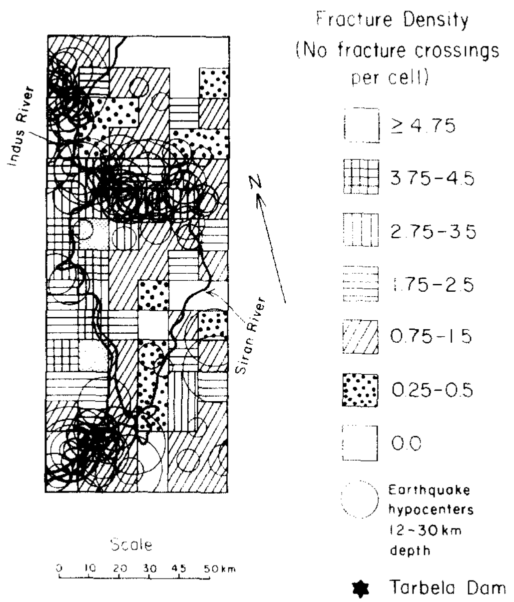



Fig. 4. Fracture-density map, Indus valley; with seismic data indicated for reference. The area is enclosed by heavy lines in Fig. 3.

tained for each of two scenes, at different seasons and hence, sun angles (Howard and Larsen, 1972; Wise 1969; Table I). The likelihood that a linear feature represents a fault or fracture increases if the feature persists, regardless of sun angle or seasonal vegetation cover. Lineaments which appear on two or more Landsat frames of the same scene are drawn on a composite map (Fig. 3). Moreover, data from five Landsat passes along a narrow corridor of the Indus River valley are used in constructing a fracture density map as follows (Fig. 4): lineaments common to three or more Landsat passes are plotted on a grid with a 10 km cell size; if a line crosses a cell edge, it counts as $\frac{1}{2}$, if it crosses a corner, it counts as $\frac{1}{4}$ and if it is entirely contained, it is considered insignificant. Fracture-orientation frequencies are also plotted at $10^0$ intervals on standard rose diagrams (Fig. 5).

*Principles of morphotectonic analysis*

When a river is in dynamic equilibrium with its surroundings, its slope, channel width and depth are adjusted to the discharge and load (Mackin, 1948). The equilibrium state of a river is a condition of balance between erosion and deposition, and when in such a state the river is termed "graded" (Davis, 1902). Any change in one of the controlling factors will displace the equilibrium in a direction that minimizes the effect of the change (LeChatelier's Principle).

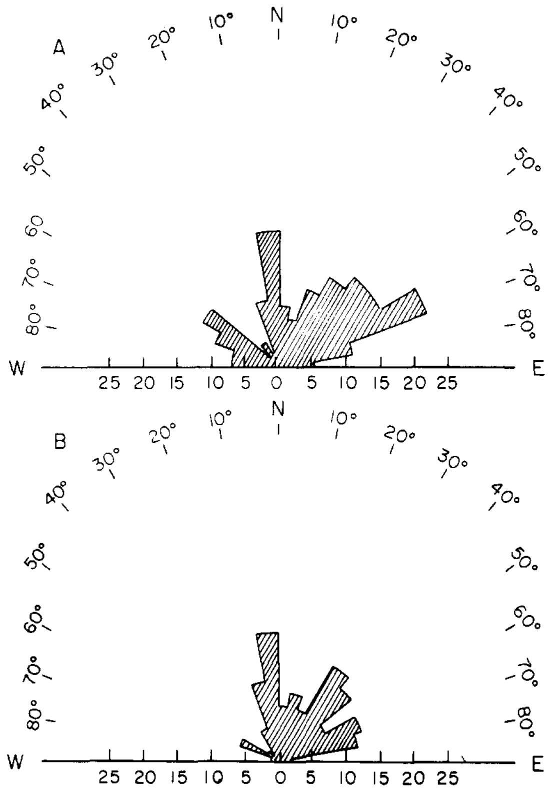



Fig. 5. A. Fracture frequency-orientation diagram, composite of Landsat frames 1065-05175, 1118-05130, 1442-05105. Hazara—Kashmir syntaxis, Indus valley (right-hand side of outlined area on Fig. 3). B. Ditto, Landsat frames 1065-05175, 2493-05005, 2673-04552. Indus valley, Peshawar Basin, Swat valley (left-hand side of outlined area on Fig. 3).

The longitudinal profile of a graded river is steepest at the source and flatterns smoothly toward the mouth (Leopold et al., 1964). Irregularities in the profile are not uncommon and are called *knickpoints*. Knickpoints generally reflect factors that tend to perturb the equilibrium state of the river. For example, a knickpoint forms when a river traverses relatively hard, erosion-resistant rocks. This knickpoint will exist only as long as the differential resistance to erosion persists. Knickpoints can also develop from eustatic lowering of the base level (usually taken as sea level). The drop in sea level steepens the gradient in the newly exposed stretch of the river and increases the capacity for downward erosion. In this case, the knickpoint marks the intersection of the new, steeper profile with the older, flatter one. This knickpoint will migrate upstream by headward erosion and eventually disappear, as the river is regraded to the lowered base level. A knickpoint may also occur where a river crosses an active fault, particularly where the uplifted block lies on the upstream side. If the fault movement ceases, the knickpoint recedes headward and is eventually obliterated. On the other hand, the knickpoint will be preserved as long as the uplift continues.

The regional base level for Himalayan rivers is the Indo-Gangetic alluvial plain. The terrigenous Siwalik sediments have accumulated continuously from the mid-Miocene through the Pleistocene, without any major break (Johnson et al., 1979). Thus lowering the base level has probably not contributed significantly to the formation of Himalayan river knickpoints. Rates of uplift in the Himalayas have remained relatively constant during this period, as shown by Siwalik deposition and by radiometric dating of metamorphic events (Mehta, 1980). It is more likely that the knickpoints are caused by differential uplift. Longitudinal profiles of Himalayan rivers can be altered by differential erosion as well as uplift, particularly where hard crystalline rocks from the lower crust are exposed on the upthrown sides of active faults, such as the Main Central Thrust.

Longitudinal stream profiles (elevation vs. distance) are obtained directly from 1 : 250,000 and 1 : 1,000,000 ONC topographic maps by plotting the distance along the river (neglecting minor bends) between consecutive contour crossings (ranging from 100-m to 300-m intervals, depending on the map scale). Thus, the river profile consists of a sequence of discrete gradients between each crossing.

The first derivative (elevation/distance = gradient) and second derivatives of the river topography are used to distinguish between major inflections or knickpoints, and insignificant topographic irregularities. In this study, a knickpoint occurs only when the ratio of two consecutive gradients is $\geqslant 3.0$ and the peak in the second derivative of elevation is at least ten times higher than adjacent values.

Hypsometric curves, which plot the distribution of surface area in a drainage basin as a function of altitude, are related to the degree of maturity of the basin. The greater the extent to which the surface has been dissected by streams, the more "mature" the basin. Continued uplift should expose more surface to denudation. Such rejuvenation of the landscape should introduce characteristic changes in the shape of the hypsometric curve and in the hypsometric integral (Strahler, 1952; 1957). The hypsometric integral, or the volume enclosed between the base level of the basin and the surface, may also reflect the age of the basin, other factors, such as lithology, being constant. Hypsometric curves for six tributaries of the Indus River and two of the Kunar River (Konar Sind) are plotted from 1 : 250,000 U.S. Army Topographic Command Maps of the Churrai, Mardan, Peshawar and Chitral quadrangles (Fig. 6).

Reversals in drainage direction (disrupted drainage) and stream piracy in the Hazara area are briefly discussed. A systematic survey using these indicators may provide suggestive evidence of recent or active tectonic deformation; however, it rarely offers unambiguous proof of tectonic activity.

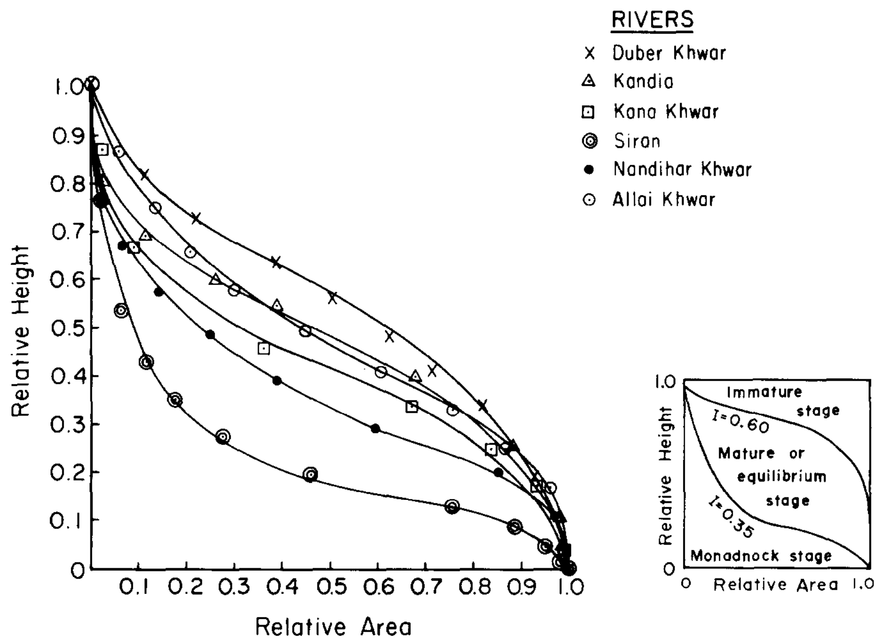



Fig. 6. Hypsometric (area-altitude curves), Indus River tributaries.

## RESULTS

### *Tectonics*

The Landsat composite lineament map has been superimposed on the seismic map derived from the Tarbela network, for hypocentral depths between 12 and 30 km (Fig. 3). (The seismicity shallower than 12 km is more scattered and tends to be confusing on a map view.) The NW-trending Indus—Kohistan seismic zone (IKSZ) crosses the upper Jhelum and Indus rivers but is not detected beyond the Swat River. The cluster of epicenters along the Indus, south of the IKSZ is the Tarbela seismic zone, TSZ. This small, but very active zone in the upper crust is above and decoupled from the Hazara lower seismic zone (HLSZ), which is much less active, but as extended as the IKSZ (Figs. 2 and 3).

The following prominent sets of lineaments are easily recognized (Figs. 3 and 5A, B).

(1) A N60°—70°E-trending set (Fig. 5A). These lineaments correspond to faults and fold axes associated with the western limb of the Hazara—Kashmir syntaxis (Calkins et al., 1975), including the Panjal Thrust (or Tanawai fault) east of Tarbela (Allen, 1974) and the Hazara Thrust (Wadia, 1931), the boundary thrust of the Hazara arc north of Rawalpindi.

(2) A N0°—10°W-trending set along the Indus River, south of the IKSZ

(Fig. 5). This set can be correlated with faults along the Indus reentrant and associated horst and/or anticline (Calkins et al., 1975; Fig. 1). N—S-trending lineaments along the Indus River have been previously recognized in the field and on aerial and satellite photographs (Gansser, 1979; Kazmi, 1979).

(3) A N60°—70° E-trending set parallel to the Swat River, that coincides in part with the proposed Main Mantle Thrust (Tahirkheli et al., 1979) or Kohistan—Pattan fault (Desio, 1979) (Fig. 5B).

(4) A N50°—60° W-trending set parallel to and slightly south of the IKSZ (Fig. 5A).

The latter set of lineaments is particularly significant because it cuts across the NE—SW structural trends of the western limb of the syntaxis (Calkins et al., 1975) and is associated with the IKSZ, the seismic expression of the Himalayan Basement Thrust in Hazara (Seeber et al., 1979). These NW-trending linear features can be followed in this direction to the Indus River where they intersect the N-trending linear elements of the Indus valley, but die out before reaching the Swat River.

The satellite lineament map (Fig. 3) is in close agreement with the results reported by Bartole (1978), especially with regard to the intersection of NW—SE and NE—SW linears across the Hazara—Kashmir syntaxis, and the prominent N—S lineaments along the Indus River.

Fracture densities range between 0 and 6 crossings/cell (see above) and are divided into seven fracture density classes (Fig. 4). The highest density of fractures (6.0) occurs at the intersection of the N—S-trending Indus River and NW-trending lineaments approximately 20 km south of the IKSZ. Another concentration of fractures (4.8) lies along the Indus River lineament, 25 km north of Tarbela, and may be related to the Indus River anticline.

It is probably significant that both the northwest lineaments and the high seismicity along the IKSZ terminate toward the northwest in the area of high fracture density centered near the Indus River at latitude 35° N (Fig. 4). Three major tectonic zones intersect in this region: the IKSZ, the Indus River horst—anticline—reentrant (IRA), and the Main Mantle Thrust (MMT). The concentration of seismicity in the Tarbela seismic zone (TSZ; Figs. 2—4) along the Indus suggests that the IRA is presently active. The MMT represents the western extension of the Indus suture (Gansser, 1979). According to Tahirkheli et al. (1979), the Kohistan island arc complex was thrusted (obducted) at the MMT onto the Indian continent. The Indus suture and MMT are presently inactive. However, the MMT may be reactivated in the vicinity of the IKSZ (see below).

*Drainage analysis*

Longitudinal profiles of the Indus River and six of its tributaries are presented in Fig. 7. Knickpoints are indicated by arrows. The geographic distribution of knickpoints on major rivers is shown in Fig. 8, and on Indus River tributaries, in Fig. 9.

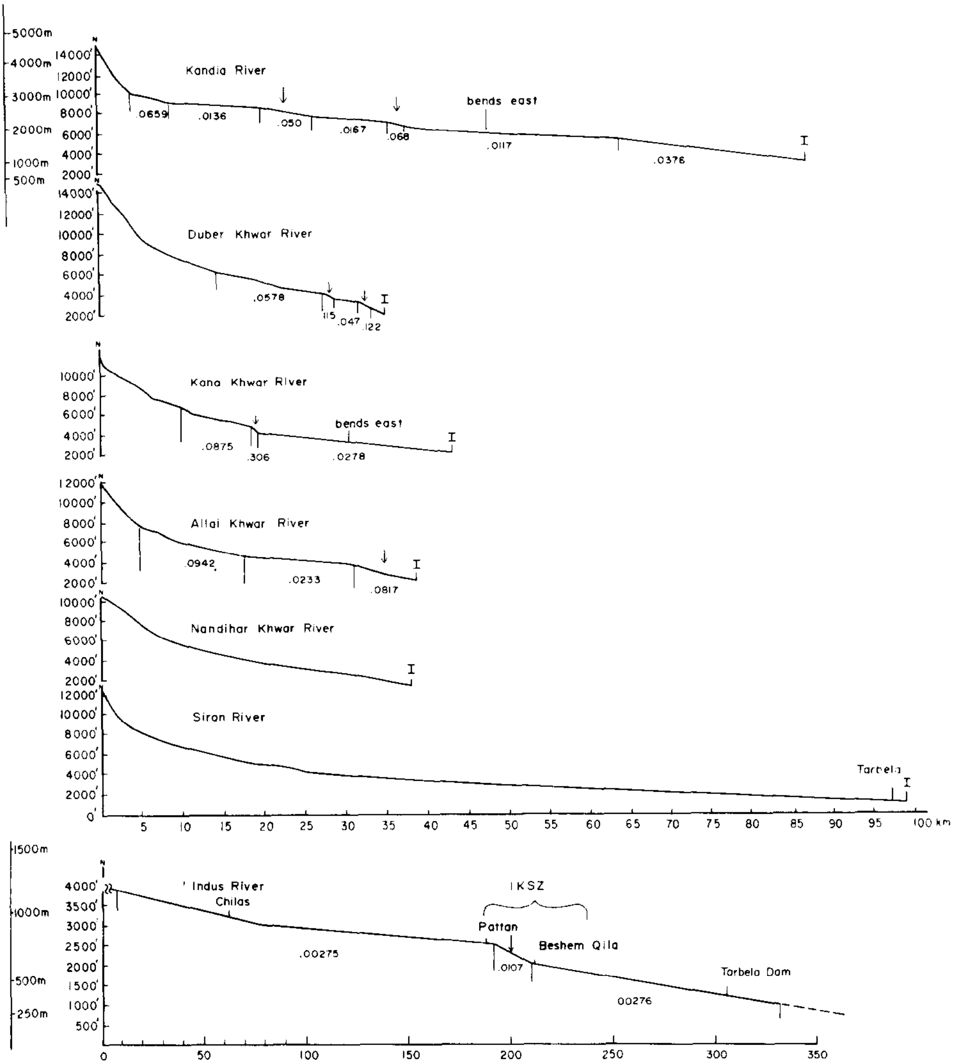



Fig. 7. Longitudinal profiles of Indus River and six tributaries. The numbers are the average gradient for each segment of the river. Knickpoints (see text) are indicated by arrows. $I$ = confluence with Indus River.

Six out of eight knickpoints, or sharp changes in slope (see above), on the major rivers (Pinjkora, Swat, Indus, Kundar, Kishanganga, Jhelum) occur on the IKSZ or its extension, and two appear slightly northeast or upstream from this seismic zone (Fig. 8). None are found southwest or downstream of the IKSZ, nor do any occur on tributaries of the Indus draining southwest of the IKSZ (Figs. 7 and 9). In contrast, only two of these eight knickpoints are

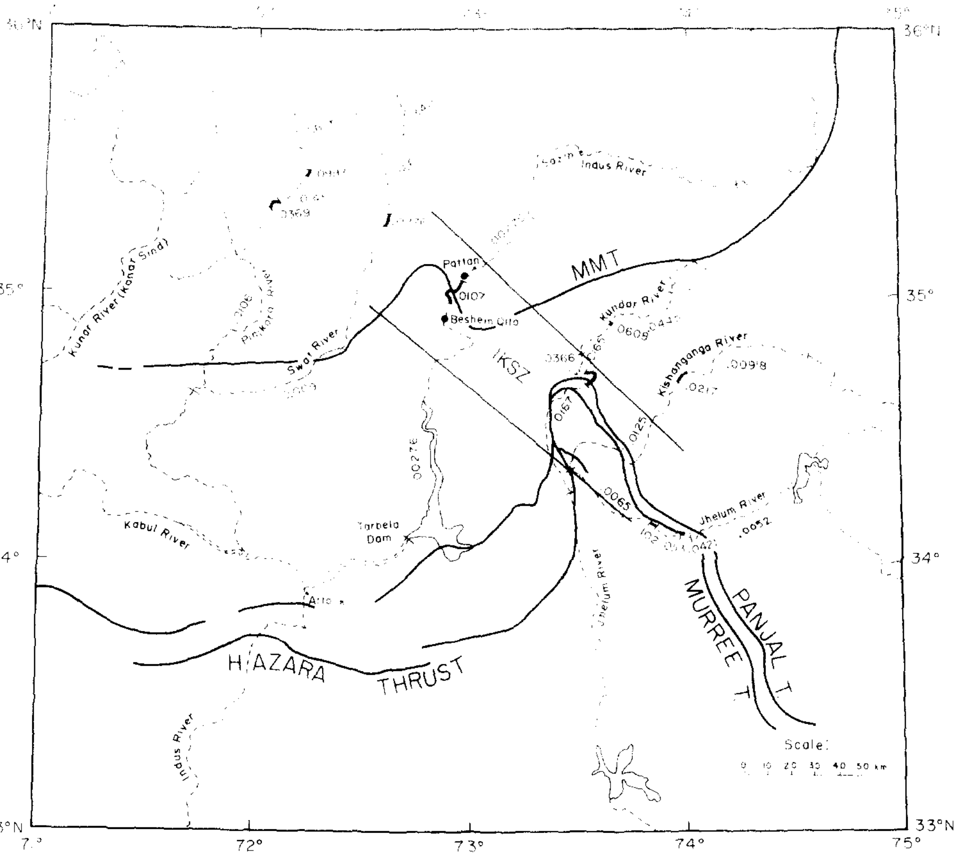



Fig. 8. Distribution of knickpoints on major rivers and their relation to the Indus–Kohistan seismic zone (IKSZ). The average gradient of a river segment is indicated by the number between thin lines. A knickpoint or segment of increased gradient is shown by heavy lines.

closely associated with major structural and lithologic boundaries: namely the Panjal Thrust on the Kundar River and the MMT on the Indus River (Figs. 1, 8, 9).

The close association of knickpoints with the IKSZ and the negative correlation between knickpoints and major surface structures suggest that these knickpoints are primarily controlled by ongoing deformation along the IKSZ. Furthermore, the concentration of knickpoints on the upthrown side and their absence on the downthrown side of this basement thrust lends additional support to this hypothesis. The active surface structures controlling the knickpoints are undeveloped and relatively young.

These observations are consistent with a detachment model, in which the sedimentary layer moves laterally above an active basement thrust at depths

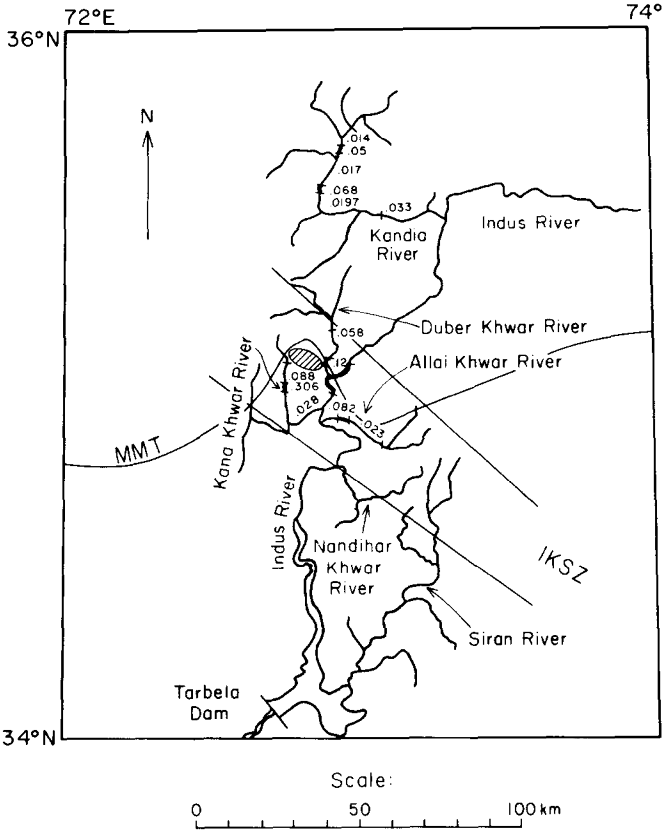



Fig. 9. Relation of knickpoints in Indus River tributaries to the IKSZ. Explanation for numbers the same as in Fig. 6. The intersection of the Main Mantle Thrust (MMT, Tahirkheli et al., 1979) with the Indus River is indicated by a bold line. The region of aftershocks from the Dec. 28, 1974 Pattan earthquake (Pennington, 1979) is drawn for reference, as the lined oval.

of 12--17 km (see above; Seeber and Armbruster, 1979; Fig. 2). Deformation in the detached sedimentary layer is time-transgressive and affects a given portion of the layer only for a relatively short time. Major structural—lithologic boundaries in the detached layer are fossil and, in general, do not reflect the active tectonics. However, these structures may be locally reactivated.

Most of the knickpoints on the Indus River tributaries (Fig. 9) are located near the MMT, suggesting a causative relationship. However, upon closer inspection, all of these steep river stretches extend south or downstream of the MMT (as mapped by Tahirkheli and Jan, 1978). The aftershock zone of the Pattan 1974, earthquake ($M$ = 6.0) lies close to the portion of the MMT that crosses the Indus River (Fig. 8). However, Pennington (1979) finds that

TABLE II

Summary of drainage morphology analysis

| Stream | Basin area ($km^2$) | Maximum relief (km) | Relief ratio [a] | Strahler stream order | Bifurcation ratio [b] | Hypsometric integral | Mean junction angle [c] (degrees) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 1—1 | 1—2 | 1—3 | 1—4 |
| *Tributaries of Indus* | | | | | | | | | | |
| Duber Khwar | 467.2 | 4.130 | 0.1090 | 4 | 3.98 | 0.550 | 43.9° | 62.6° | 80.1° | 90.4° |
| Kandia | 2477.2 | 5.334 | 0.0759 | 4 | 5.53 | 0.472 | 50.7 | 68.8 | 79.5 | 86.8 |
| Kana Khwar | 681.7 | 3.688 | 0.0768 | 5 | 4.59 | 0.416 | 46.3 | 62.5 | 74.4 | 94.0 |
| Allai Khwar | 471.2 | 3.688 | 0.1004 | 4 | 4.39 | 0.490 | n.c | n.c | n.c | n.c |
| Nandihar Khwar | 536.9 | 3.215 | 0.0919 | 5 | 3.17 | 0.371 | n.c | n.c | n.c | n.c |
| Siran | 1809.4 | 3.993 | 0.0114 | 5 | 4.59 | 0.229 | 56.0 | 67.6 | 70.2 | 82.8 |
| *Tributaries of Konar Sind* | | | | | | | | | | |
| Landay Sin | 3100.2 | 4.900 | 0.0576 | 3 | 7.28 | 0.522 | 92.3 | 97.1 | 89.5 | — |
| Pec Dora | 3780.0 | 4.910 | 0.0510 | 4 | 3.44 | 0.465 | 98.8 | 76.5 | 93.6 | 92.57 |

[a] The relief ratio is the ratio of the total relief (highest elevation—lowest elevation) to the longest linear dimension of the drainage basin.

[b] The bifurcation ratio is the antilog of the slope of the line relating stream order to number of streams of that order.

[c] The mean junction angle is the arithmetic average of angles between all pairs of streams of given orders, as measured from a map.

n.c. = not computed.

these aftershocks are 12—15 km deep, lie near the detachment and belong to the IKSZ. Moreover, the 1974 aftershocks occur significantly south of the MMT (Fig. 9). Thus, the Pattan earthquake can only be indirectly related to the MMT. Although local reactivation of the MMT and differential erosion across this fault zone are both possible, significant differential uplift across the MMT within the last 15 m.y. is unlikely, as suggested by data from fission track dating (P. Zeitler, personal communication).

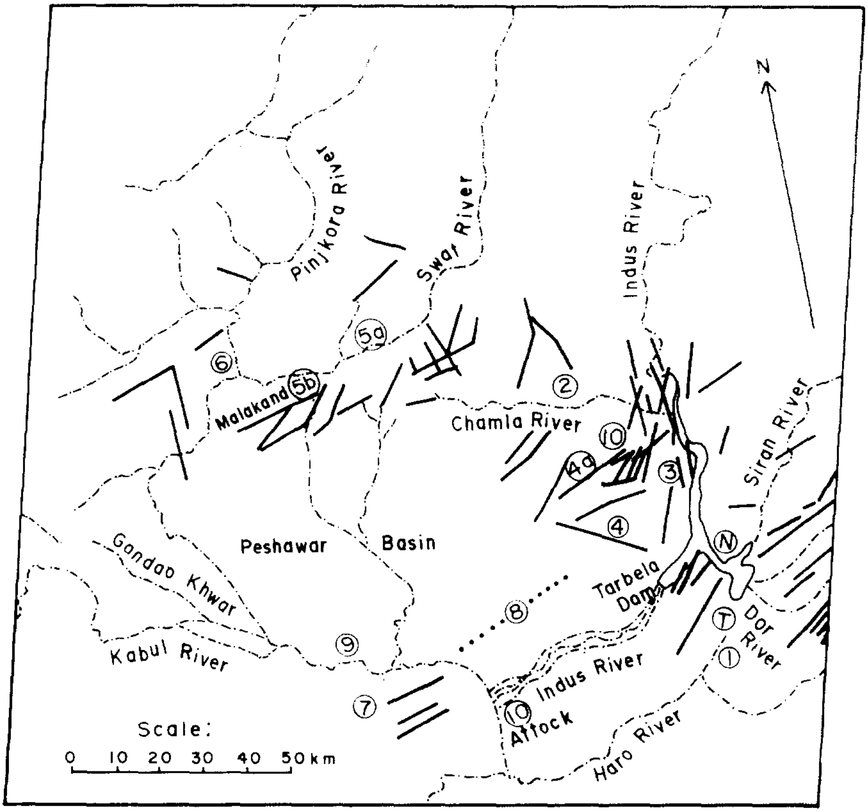
Similarly, the knickpoints on the Kundar River may be associated with reactivation of the Panjal fault and/or differential erosion across this fault (Fig. 8).

Ultramafic rocks outcrop along the MMT in the Indus valley (Fig. 1). These ultramafic rocks may be more erosion-resistant than the rocks on the downfaulted and downstream side of the MMT. Therefore, differential erosion may be partially responsible for the knickpoints on the Indus and its tributaries (Figs. 7, 8, 9).

Hypsometric curves are obtained for six tributaries of the Indus, in northern Hazara and 2 on the Kunar River in Afghanistan. Results are shown in Fig. 6. Hypsometric integrals and other drainage basin parameters are presented in Table II. According to Strahler (1952), immature basins have integrals greater than 60%, mature or equilibrium-stage basin integrals lie between 35 and 60%, while very eroded basins (Monadnock stage) show integrals below 35%. Hypsometric integrals for the eight streams analyzed range between 0.229 and 0.550 (mean = 0.439, $\sigma$ = 0.102). All streams fall into the mature range, except for the Siran, which belongs to the Monadnock stage. Among the Indus tributaries examined, only the Siran drains south of the IKSZ. The Duber Khwar River, which crosses the MMT (Fig. 9; Tahirkheli et al., 1979) and the Pattan, 1974, aftershock zone has the highest integral, 0.550, the highest relief ratio, and is the least mature of the rivers analyzed.

### *Morphotectonic analysis*

Anomalies in drainage patterns can provide clues regarding tectonic deformation. The following observations refer to Landsat frames 2673-04552, 2493-05005 (Fig. 10). It has been suggested that the Indus River formerly drained southward through the Haro River valley (Fig. 10: *1*) (Siddiqui, personal communication). An alternative interpretation is that the Siran and Dor rivers were successively captured by the Indus away from the Haro Basin. This latter hypothesis is consistent with detailed fault movements deduced from seismicity in the Haripur Basin. The siran River flows through a gap marked by subsidence along normal faults (*N* in Fig. 10) (Armbruster et al., 1978) while at *T* shallow thrusting in the Haro River valley is causing uplift relative to the Siran gap (Farhatulla, personal communication). Furthermore, recent river terraces in the hills between the Indus and Haro valleys are tilted toward the northeast.




(Landsat frame 2673-04552)

Fig. 10. Location of drainage pattern anomalies, Peshawar Basin and environs. For clarity, only those lineaments (solid lines) surrounding the Peshawar Basin are redrawn from Fig. 3. Numbers refer to areas discussed in the text. $T$ = thrusting, $N$ = normal faulting (from Armbruster et al., 1978). Dot-dash lines are rivers; the Swabi—Nowshera ridge is shown by a dotted line.

The Chamla River (*2* in Fig. 10) drains east toward the Indus, rather than the shorter distance south toward the Peshawar Basin, suggesting uplift in the Mahaban Ghar Mts. (Fig. 10; *10*). Landsat lineaments (Fig. 10; *3*, *4*) bound the Mahaban Ghar Mts. to the east and south. A high concentration of fractures and microearthquakes occur in this area. Seismicity patterns suggest motion along these inferred faults, leading to uplift in these mountains (Seeber et al., 1979).

The Swat River is clearly antecedent to the mountains on the western edge of the Peshawar Basin. Uplift in these mountains has caused ponding and deposition on the broad flood plain above Batkhela (Fig. 10; *5a*). Headward erosion of the stream in the Malakand valley could eventually capture the Swat River. However, the topographic barrier between the Swat and Malakand valleys may be rejuvenated by slip on a fault that coincides with this ridge, as inferred from two prominent NE—SW Landsat lineaments (Fig. 10; *5b*). The southernmost of the two lineaments may correspond to the tectonic contact between the Dargai ultramafic body and sericitic calc-schists at Herushah (Gansser, 1979).

Differential motion has occurred in the Pashawar Basin (Kazmi, 1979). A topographic ridge, *8* in Fig. 10, west of the Indus River, referred to here as the Swabi--Nowshera ridge, appears dry and unvegetated, whereas the lowlying portion of the basin further west is vegetated and cultivated. The Kabul River changes from a braided stream to a shallow narrow valley (at Fig. 10; *9*) as it cuts through this ridge and the Star Ghar Mts. (Fig. 10; *7*). The narrow section of the Kabul River truncates the braided Indus River at Attock (Fig. 10; *10*). This peculiar drainage pattern suggests that the Swabi—Nowshera ridge is rising with respect to the Peshawar Basin on the west and the Indus valley on the east.

The Murree fault (Calkins et al., 1975; also called the Jhelum fault, Kazmi, 1979; Hazara Thrust, Armbruster et al., 1978) is the extension of the MBT into the Hazara arc region. This fault has structurally controlled the N—S segments of the Kunhar, Kishanganga and Jhelum rivers. The Kunhar and Kishanganga rivers bend at the syntaxial axis. However, it may be significant that the prominent bends of these rivers also occur close to where they intersect the IKSZ. The NW—SE part of the Jhelum valley is approximately aligned along the IKSZ, as is the right angle bend of the Indus River, just south of Beshem Qila, and these may also be controlled by this basement structure.

Pilgrim (1919) proposed that the Siwalik boulder conglomerates of Pliocene—Pleistocene age were deposited by a river that flowed from southeast to northwest along the foot of the rising Himalayas. Accordingly, peculiar V-bends in many of the major Himalayan rivers, including the Jhelum, are attributed to this ancestral drainage; the north-northwestern arms of the V's correspond to former tributaries flowing southwest into the ancestral river. Uplift northwest of Jammu, caused disruption and reversal of the drainage. Through a series of river captures, the present drainage pattern became established (Pilgrim, 1919; Pascoe, 1919). Recent sedimentological studies cast doubts on the existence of the so-called Indobrahm River (Gill, 1951; Tandon, 1972; Visser and Johnson, 1978; Johnson et al., 1979). These studies show that N—S flowing rivers, as at present, could have supplied the Siwalik sediments. One aspect of the older theory may still hold, however: the drainage divide between the watersheds of the Indus and Jhelum rivers near the town of Murree has been only recently established, since the Jhelum River once flowed into the Soan River (Fig. 1). Recent uplift near Murree has diverted the lower Jhelum to its present course, while the Soan, deprived of its former discharge, is now an underlift river (Pascoe, 1919). This hypothesis is supported by the results of Bartole (1978) which indicate "rejuvenation", presumably by uplift, in the area between Islamabad and the town of Jhelum.

## CONCLUSIONS

(1) Landsat imagery shows a N—S-trending set of lineaments along the Indus River and NW-trending lineaments roughly aligned with the IKSZ. Fractures are concentrated at the intersection of these two lineaments trends, less than 20 km south of IKSZ, and along the Indus River 25 km north of Tarbela. Only the NW-trending Landsat lineament set is obviously associated with current seismic activity occurring in the lower crust below the detachment. The lineaments along the Indus River are probably related to the Indus anticline—horst and associated reentrant (Calkins et al., 1975) which is recognized between Tarbela Dam and Beshem Qila (Fig. 3). The Tarbela seismic zone may be indirectly related to this feature.

(2) Longitudinal profiles of the Indus tributaries show knickpoints in the area between Pattan and Beshem Qila, slightly north of the IKSZ in an area of high seismicity. Two streams draining south of the IKSZ show no knickpoints. A tectonic origin for the knickpoints is suggested by the proximity to the IKSZ. Knickpoints only occur upstream (northeast) of the IKSZ, indicating that the northeastern side is uplifting with respect to the southwest side of the IKSZ.

(3) Hypsometric curves of Indus River tributaries near the IKSZ indicate, that while all of the basins are "mature", the Siran Basin, the only one of these basins draining south of the IKSZ, is "overmature", i.e., more strongly eroded. It seems unlikely that the Siran profile can be explained by either a relatively early age of uplift for this basin, or by a relatively low resistance to erosion. Alternatively, a differential rate of uplift along the Siran drainage, higher toward the source area on the IKSZ, and lower downstram, southwest of the IKSZ, may also give the basin a more "eroded" appearance. The latter explanation is consistent with differential uplift at the IKSZ, suggested by the distribution of knickpoints (see above).

(4) Landsat imagery provides examples of disrupted drainage and river capture, which can be related to recent tectonism. From Landsat, the Peshawar Basin appears bounded on the north by NW- and NE-trending faults. The seismic data indicates a similar fault pattern where the movement is consistent with N—S compression (Armbruster et al., 1978). Several of the Landsat lineaments correspond directly with seismic lineaments: e.g. compare Landsat lineaments *4* and *4a* (Fig. 10) with seismic lineaments 12 (also 16) and 13, respectively, in fig. 10 of Armbruster et al. (1978). Furthermore, the seismic data suggest that the Mahaban Ghar Mts. (*10*, in Fig. 10) are an uplifted block, bounded on the east and south by thrust faults (lineaments *3* and *4*, Fig. 10). The uplift hypothesis is further supported by the drainage patterns.

(5) In general, linear features obtained from Landsat satellite imagery and

river profiles are found to be diagnostic of a basement thrust, active beneath a decollement, and which otherwise has no direct surface expression. The major basement thrust does not appear at the surface as a single fault, with a large displacement. Instead, it is manifested as a relatively wide zone with a large number of subparallel fractures. The displacement in the detached sedimentary layer may be taken up by motion along these faults and by folding.

## ACKNOWLEDGMENTS

This research was supported by NASA Cooperative Agreement NCC 5-16, National Science Foundation grant EAR 77-15187, and U.S. Geological Survey grant 14-08-0001-16749. We appreciate the helpful suggestions and comments of Klaus Jacob, John Armbruster and Gary Johnson. The TAMS Engineers and Architects, and Water and Power Development Authority of Pakistan are thanked for their continued support in the field operations.

## REFERENCES

Allen, C.R., 1974. Preliminary Report on Visit to Tarbela Dam and Vicinity, 7—13 August, 1974 (unpubl. manuscipt).

Armbruster, J., Seeber, L. and Jacob, K.H., 1978. The northwestern termination of the Himalayan mountain front: active tectonics from microearthquakes, J. Geophys. Res., 83: 269—282.

Bakr, M.A. and Jackson, R.D., 1964. Geological Map of Pakistan, 1: 2,000,000: Quetta. Geological Survey of Pakistan.

Bartole, R., 1978. Structural lineaments of the Central Asian orogenic syntaxis from Landsat imageries. Accad. Naz. Lincei, Ser. VIII, LXIV: 485—489; 614—619.

Calkins, J.A., Offield, T.W., Abdullah, S.K.M. and Ali, S.T., 1975. Geology of the southern Himalaya in Hazara, Pakistan, and adjacent areas. U.S. Geol. Surv., Prof. Pap., 716-C.

Davis, W.M., 1902. Base level, grade and peneplain. J. Geol., 10: 77—111.

Desio, A., 1964. Geological Tentative Map of the Western Karakoram (1 : 500,000) Inst. Geologia, Univ. Milano.

Desio, A., 1974. Geological reconnaissance in the middle Indus valley between Chilas and Besham Qila, Pakistan. Boll. Soc. Geol. It., 93: 345—368.

Desio, A., 1979. Geologic evolution of the Karakorum. In: A. Farah and K.A. DeJong (Editors), Geodynamics of Pakistan. Geol Survey of Pakistan, pp. 111—124.

Ebblin, C., 1976. Tectonic lineaments in Karakorum, Pamir and Hindu Kush from ERTS imageries. Acad. Naz. Lincei, Ser. VIII, LX: 246—253.

Gansser, A., 1964. Geology of the Himalayas. Interscience, London, 289 pp.

Gansser, A., 1979. Reconnaissance visit to the ophiolites in Baluchistan and the Himalaya. In: A Farah and K.A. DeJong (Editors), Geodynamics of Pakistan. Geol. Survey of Pakistan, pp. 193—213.

Gill, W.D., 1951. The stratigraphy of the Siwalik Series in the northern Potwar, Punjab, Pakistan. J. Geol. Soc. London, 107: 375—394.

Howard, K.A. and Larsen, B.R., 1972. Lineaments that are artifacts of lighting. Apollo 15 Prelim. Sci. Rep., Part G, NASA SP-289.

Johnson, G.D., Johnson, N.M., Opdyke, N.D. and Tahirkheli, R.A.K., 1979. Magnetic reversal stratigraphy and sedimentary tectonic history of the Upper Siwalik Group, eastern salt range and southwestern Kashmir. In: A Farah and K.A. DeJong (Editors), Geodynamics of Pakistan, Geol. Survey of Pakistan, pp. 149—165.

Kazmi, A.H., 1979. Active fault systems in Pakistan. In: A. Farah and K.A. DeJong (Editors), Geodynamics of Pakistan. Geol. Survey of Pakistan, pp. 285—294.

Leopold, L.B., Wolman, M.C. and Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Fransisco, Calif., 522 pp.

Mackin, J.H., 1948. Conception of the Graded River, Geol. Soc. Am. Bull., 59: 463—512.

Mehta, P.K., 1980. Tectonic significance of the young mineral dates and the rates of cooling and uplift in the Himalaya. Tectonophysics, 62: 205—217.

Pascoe, E.H., 1919. Early history of the Indus, Brahmaputra and Ganges. Q. J. Geol. Soc., 75: 138—159.

Pennington, W.D., 1979. A summary of field and seismic observations of the Pattan earthquake, 28 Dec., 1974. In: A Farah and K.A. DeJong (Editors), Geodynamics of Pakistan. Geol. Survey of Pakistan, pp. 143—147.

Pilgrim, G.E., 1919. Suggestions concerning the history of the drainage of northern India, arising out of a study of the Siwalik boulder conglomerate. J. Asiat. Soc. Bengal., 15(5): 81—99.

Seeber, L. and Armbruster, J., 1979. Seismicity of the Hazara arc in northern Pakistan: décollement vs. basement faulting. In: A. Farah and K.A. DeJong (Editors), Geodynamics of Pakistan, Geol. Survey of Pakistan, pp. 131—142.

Seeber, L. and Jacob, K.H., 1977. Microearthquake survey of northern Pakistan: preliminary results and tectonic implications. Proc. C.N.R.S. Symp. Geol. Ecology Himalayas, Paris, pp. 347—360.

Seeber, L., Quittmeyer, R. and Armbruster, J., 1979. Seismotectonics of Pakistan: a review of results from network data and implications for the Central Himalaya. In: P.S. Saklani (Editor), Structural Geology of the Himalaya. Today and Tomorrow's Printers and Publishers, New Delhi, pp. 361—392.

Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Am. Bull., 63: 1117—1142.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Trans. Am. Geophys. Union, 38: 913—920.

Tahirkheli, R.A.K. and Jan, M.Q., 1978. A Preliminary Geologic Map of the Kohistan and the Adjoining Areas, North Pakistan, Univ. Peshawar Publ.

Tahirkheli, R.A.K., Mattauer, M., Proust, F. and Tapponier, P., 1979. The India Eurasia suture sone in northern Pakistan: synthesis and interpretation of recent data at plate scale. In: A. Farah and K.A. DeJong (Editors), Geodynamics of Pakistan. Geol. Survey of Pakistan, pp. 125—130.

Tandon, S.K., 1972. Heavy minerals and quartz axial ratios as provenance indicators in Siwalik sediments around Ramnagar, Kumaun Himalaya. Himalayan Geol., 2: 206—221.

Visser, C.F. and Johnson, G.D., 1978. Tectonic control of Late Pliocene molasse sedimentation in a portion of the Jhelum re-entrant, Pakistan. Geol. Rundsch., 67: 15—37.

Wadia, D.N., 1931. The syntaxis of the North-West Himalaya — its rocks, tectonics, and orogeny. India Geol. Surv. Rec., 65, Pt. 2: 189—220.

Wadia, D.N., 1961. Geology of India. McMillan, London, 3rd. ed.

Wise, D.U., 1969. Pseudo-radar topographic shadowing for detection of subcontinental sized fracture systems. Proc. Int. Symp. Remote Sensing and Environments, 6th, Ann Arbor, pp. 603—620.